Development of the
Free-space Optical Communications Analysis Software

Muthu Jeganathan, G. Stephen Mecherle[a] and James R. Lesh

Jet Propulsion Laboratory, MS 161-135, 4800 Oak Grove Dr., Pasadena, CA 91109

[a]Laser Diode Systems Corp., Hawthorne, CA 90250

ABSTRACT

The Free-space Optical Communication Analysis Software (FOCAS) was developed at the Jet Propulsion Laboratory (JPL) to provide mission planners, systems engineers and communications engineers with an easy to use tool to analyze optical communications link. The FOCAS program, implemented in Microsoft Excel, gives it all the power and flexibility built into the spreadsheet. An easy-to-use interface, developed using Visual Basic for Applications (VBA), to the spreadsheet allows easy input of data and parameters. A host of pre-defined components allow an analyst to configure a link without having to know the details of the components. FOCAS replaces the over-a-decade-old FORTRAN program called OPTI widely used previously at JPL. This paper describes the features and capabilities of the Excel-spreadsheet-based FOCAS program.

Keywords: Optical Communications, Laser Communications, Free-space, Link budget, Link table, Link analysis

1. INTRODUCTION

To keep up with the frequently-requested applications studies by JPL mission planners, an automated analysis tool (computer program) called OPTI was created at JPL in the early 1980's. OPTI was developed to run on what were then new (286) personal computers. It would either determine the link margin resulting from a set of specified parameters for the transmitter terminal, the propagation path, the receiver terminal and the background conditions, or it would solve for the value of a single parameter (e.g. transmit optical power) that was required to achieve a specified overall link margin. The original OPTI program was restricted to the analysis of "Photon-counting" detection systems with PPM modulation, and after initial development and testing, was made available to other parties through the NASA COSMIC software archive. Several improved versions of OPTI were also developed. The most important (OPTI-APD) resulted from the modification of OPTI to include Avalanche Photodiode Detectors (APDs) instead of photon-counting detectors for reception. A variant of OPTI-APD called "TOLER" was also developed which used the basic OPTI-APD shell, but allowed the bookkeeping of favorable and adverse parameter tolerances. Another version called "HET" was also developed to handle a very simplified form of heterodyne optical signal detection. All of the OPTI (or derivative) programs were developed to handle essentially deep space-to-ground links, and required special techniques to trick the programs for analysis of other link applications (e.g. space-space links, uplinks, etc).

By the mid 1990's, it became clear that all of these tools were outdated, both from the standpoint of the platforms on which they operated and from the restricted nature of their applications validity. Additionally, the increased interest and acceptance of optical communications made it clear that design tools that could be disseminated to system designers, not just optical communications experts, would be required. Accordingly, a task was started to begin the development of a trilogy of analysis tools. One (set) of these tools would involve the computationally-intense detailed analyses that would be performed by the optical communications specialists. The second (set) would be simulation-based and would be used by optical communications design engineers. The third would be a user-friendly program that would allow the system engineers, or other interested non-experts, to efficiently evaluate optical communications links. The Free-space Optical Communications Analysis Software (FOCAS) is the third item in that trilogy and is the subject of this paper. Another program to analyze the acquisition and tracking (Acq/Trk) performance of an optical communication system is currently under development to complement FOCAS.

Send correspondence to Muthu Jeganathan at muthu@altair.jpl.nasa.gov or Steve Mecherle at LDSCsm@aol.com

Figure 1. Block diagram view

We decided to write FOCAS in MS Excel for several reasons. First, Excel, part of the Microsoft Office Suite, is a common software that most computer users have and are familiar with. Second, we believed Excel would enable us to develop a single application for both PCs and Macs. Excel further allowed easy development of graphical user interface (GUI) through Visual Basic for Applications (VBA). Finally, all the power of Excel such as auto-calculation, built-in mathematical and statistical functions and "goal seeking" could be used in FOCAS. For example, the "goal-seeking" function of Excel is used in FOCAS to find roots of complex equations iteratively. For these reasons Excel was chosen over other software packages such as Visual C++ and Matlab. After a preliminary version of FOCAS was completed, we discovered that FOCAS was incompatible with Macs and Excel'97 for PCs. This, apparently, is due to the differences in the way VBA behaves on different platforms. Thus for the time being, FOCAS functions properly only on PCs with Excel 5.0/7.0.

In this article, we provide a brief description of the software, describe the capabilities and features of FOCAS, and provide a sample Link table showing the output generated by FOCAS. Details of the equations that went into the calculation of link tables are in the FOCAS Technical Manual while information on how to use the software is described in the FOCAS User Manual.

2. SOFTWARE OVERVIEW

When FOCAS (i.e., focas.xls file) is opened in Excel, the user sees a block diagram view of an optical communications link as shown in Figure 2. The blocks appear as buttons and when pressed typically bring up dialog boxes that let users view and edit parameters corresponding to the block. The buttons on the left correspond to components that make up the transmitter. Similarly, the buttons on the right correspond to components that make up the Receiver.
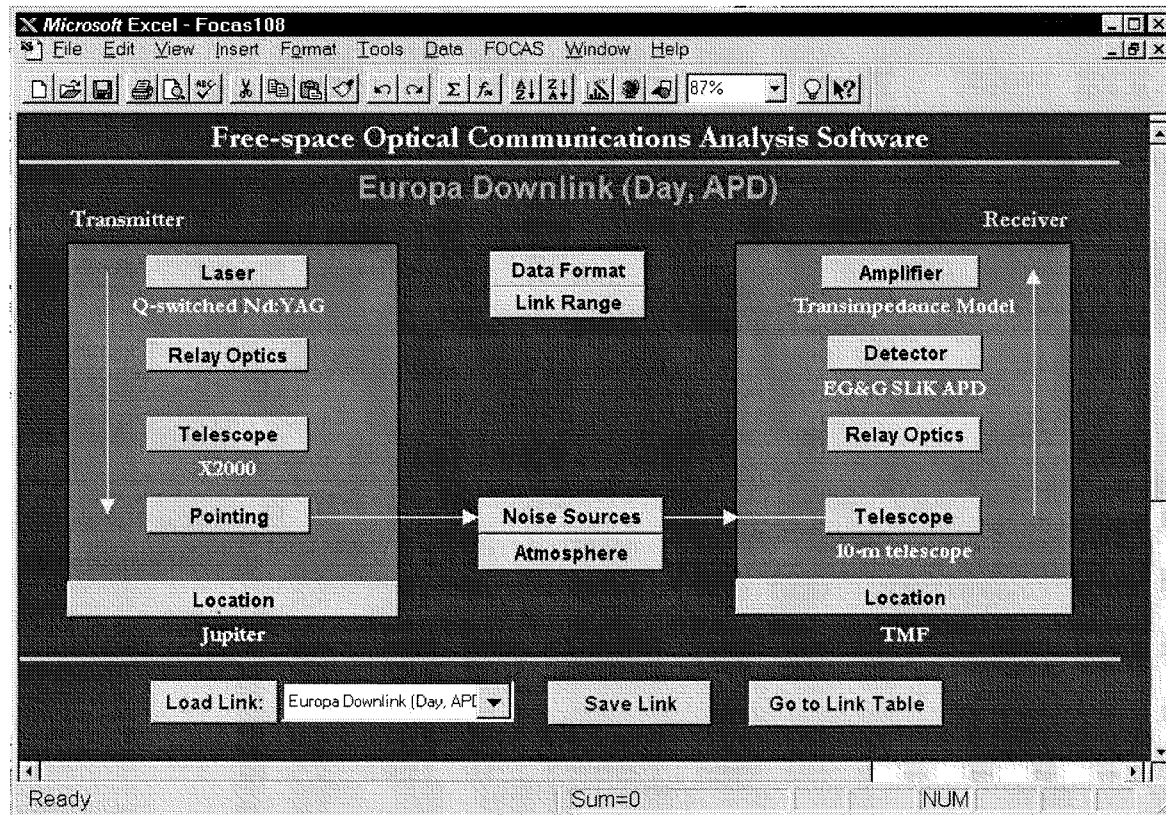
Figure 1

Figure 2. Dialog box seen when a user clicks on the Data Format button shown in Figure 1.

The buttons in the center access the link and channel parameters while the buttons in the bottom allow the user to load/save parameters and view the link table.

In a typical scenario, the user specifies all of the link parameters by clicking on the buttons, saves the link and pushes the "Go to Link Table" button to see the output of FOCAS. As an example, figure 2 shows the Data Format dialog box through which parameters such as data rate, bit-error-rate, modulation type and coding scheme can be specified. Often the user is not familiar with all the parameters associated with a component. Thus, where appropriate, we have included a database of commercial components that the user can select without specifying the individual parameters. The FOCAS program then loads in the parameters for that component from the database. Furthermore, when the user clicks the "OK" button on the dialog boxes, parameters are checked against a list of minimum and maximum allowed values. If the parameter values are out of range, an error message pops up and the user is forced to change the value before proceeding further. This check ensures parameters are not set to unphysical/impossible values.

3. FOCAS OUTPUT

Once all parameters have been entered through the dialog boxes, the user can view the link table by pressing the button labeled "Go to Link Table". FOCAS then displays a new spreadsheet (see Table 1) with the input parameter values and the calculated values. The Link Table is divided into two different sections, a Link Summary section and a Detailed Link section. The Link Summary provides a general overview of the link. Only a few link parameters are listed in the Link Summary, along with the overall link margin. Among the parameters included are link range, data rate, bit error rate, transmit power, received power, required power, transmitter gain, receiver gain, and terms which account for losses through the path. The Detailed Link section, which follows the Link Summary section, consists of several subsections (Transmitter, Channel, Receiver, Link Margin, Coding, Required Signal Power Calculation, Background Radiation), each of which provides in depth information on the link.

Almost all the cells in the Link Table are locked, which prohibits the user from inadvertently changing some values which are dependent variables that are calculated. At the same time, it is inconvenient to have the user go back to the dialog boxes everytime a common parameter value needs to be modified. Thus, certain parameters shown in green (such as link range, data rate, laser average power, transmit beamwidth and receive aperture diameter) are allowed to be changed right in the Link Table spreadsheet. The auto-calculation feature of Excel then updates the Link Table. This feature provides an interactive means of designing a link.

Data Format

Data rate: `100`   ◉ Kbps   ○ Mbps   ○ Gbps   OK

Required BER: `.000001`   Cancel

Modulation

◉ Pulse-position modulation (PPM)   Laser-modulation extinction ratio: `0.000001`

   Alphabet size: `256` ▾   Pulsewidth to slot-width ratio: `0.8`

○ On-Off Keying (direct detection)

Coding

○ none   N   `255` ▾

◉ Reed-Solomon code   K   `224`

                                         Calculated Rate: .87843137

Figure 2

Another important feature in the Link Table spreadsheet is that it displays several "Error" and "Warning" messages. Theses messages appear in red just to the left of the parameter value. If these messages are present, input parameters should be adjusted such that the problem denoted by the error message disappears. For example, an error occurs if the user tries to enter a beamwidth that is smaller than the diffraction limit for a selected telescope diameter. Some of the messages are mere warnings, and thus the user should take care in determining whether to alleviate the problem or proceed with the current warning. For example, a "Spoiled beamwidth" message is displayed when the user enters a beamwidth larger than the diffraction limited beamwidth.

4. FEATURES AND CAPABILITIES

FOCAS has been designed to handle a completely generalized direct detection laser communication system. As a result some numerical integration and root-finding algorithms are required. For example, numerical integration is used for M-ary PPM BER and Rician pointing fade calculations while series summation is used for Reed-Solomon Coding [1]. Following is a partial list of FOCAS's general direct-detection features.

- Modulation schemes: Currently, only the popular On-Off Keying (OOK) and M-ary Pulse-Position Modulation (PPM) are supported in FOCAS. Manchester coding (binary PPM) is a special case of M-ary PPM. OOK is best suited for very high data rate near-Earth link while PPM is best for moderate to low data rates using lasers with energy storage, such as deep space to Earth links. The required signal power calculation includes the effect of finite extinction ratio on the transmitter, and automatically uses the optimum APD gain.

- Coding: Reed-Solomon (RS) Code with arbitrary choice of code-word length and number of information symbols.

- Lasers: Energy-storage based lasers (eg. Q-switched and cavity dumped lasers), current or externally modulated CW lasers

- Transmitter and Receiver: transmitter and receiver gain for near-diffraction limited beam profiles are calculated based on the results of Klein and Degnan [2,3], which selects the optimum Gaussian beamwidth-to-aperture-diameter for given secondary obscuration. Additionally, the user can use a Gaussian far-field beam profile. The effect of transmit telescope wavefront quality is incorporated in the Strehl ratio.

- Detectors: PIN Photo Detectors (PD), Avalanche Photo Diode (APD), Photo Multiplier Tubes (PMT) including look-up tables for the wavelength dependent quantum efficiency.

- Amplifiers: Built into FOCAS are models for transimpedance and high-impedance pre-amplifier. These models determine the preamp noise-equivalent-current (NEI) from the bandwidth required for the link and detector characteristics. The NEI model is based on the work of Smith & Personick, Muoi and MacGregor *et. al.* and was generalized to the time domain for compatibility with M-ary PPM [4–6]. The user can, of course, choose to select an amplifier from the database with a known NEI instead of the model.

- Other: Wavelength and zenith angle dependent atmospheric transmission data, and wavelength dependent sky radiance data obtained from MODTRAN [7] is used to achieve better accuracy at different wavelengths. FOCAS also calculates and displays burst error probability due to pointing jitter and bias, using a Rician probability model. Link range is automatically determined for transmitter/receiver locations in the database.

5. CONCLUSIONS

We have completed development of an user-friendly Excel program to analyze optical communication links. The software has been in use at JPL (internal only) for about six months, which can be considered an extended beta testing. A user manual has been written and the technical manual is nearing completion. Another iteration of software and manual updates is required before the software can be distributed. In future releases of FOCAS, we plan to a) add the effects of atmosphere on the link; b) add non-Gaussian APD statistics; c) add convolutional error encoding; d) enlarge component databases; e) add planetary and star background sources database; and f) add component/subsystem mass and power estimates for flight terminals. In addition, we plan to integrate FOCAS with another software being developed at JPL called ATLAS (Acquisition and Tracking Link Analysis Software).

ACKNOWLEDGMENTS

REFERENCES

1. G. S. Mecherle, *Maximized data rate capability for optical communication suing semiconductor devices with pulse position modulation.* PhD thesis, University of Southern California, Los Angeles, 1986.
2. B. J. Klein and J. J. Degnan, "Optical antenna gain. 1: Transmitting antennas," *Appl. Opt.* **13**(9), pp. 2134–41, 1974.
3. J. J. Degnan and B. J. Klein, "Optical antenna gain. 2: Receiving antennas," *Appl. Opt.* **13**(9), pp. 2397–2401, 1974.
4. R. G. Smith and S. D. Personik, "Receiver design for optical fiber communications systems," in *Semiconductor devices for optical communications*, H. Kressel, ed., ch. 4, Springer Verlag, New York, 1980.
5. A. D. MacGregor, B. Dion, and R. J. McIntyre, "High sensitivity, high data rate receivers for ISL using low-noise silicon APD's," *SPIE Proceedings* **1131**, pp. 176–186, 1989.
6. V. Muoi, "something," *something* , 1984.
7. A. Berk, L. Bernstein, G. Anderson, P. Acharya, D. Robertson, J. Chetwynd, and S. Adler-Golden, "MODTRAN cloud and multiple scattering upgrades with applications to AVIRIS," *Remote Sensing of Environment* , 1998. Accepted for publication.

Table 1

Europa Downlink (Day, APD)

Link Summary

Link Range	**8.98E+08**	km		6.00 AU	
Data rate	**1.00E+02**	kbps	PPM (M = 256)		
Coded BER	**1.00E-06**		Reed-Solomon Coding		
Bit rate	113.84	kbps	(N = 255 & K = 224)		
Uncoded BER	9.38E-03				
Transmit power	3.00	W average	10.54 kW (peak)	70.23	dBm
Transmit losses	68.4	% transmission		-1.65	dB
Transmitter gain	6.3	urad beamwidth		117.23	dB
Pointing losses				-0.97	dB
Space loss				-380.51	dB
Atmospheric losses	62.2	% transmission		-2.06	dB
Receiver gain	10.00	m aperture diameter		149.23	dB
Receiver optics losses	46.1	% transmission		-3.36	dB
Received signal	6.96E+02	photons/puls	6.50 nW (peak)	-51.87	dBm
Background signal level	3.98E+02	photons/slot	2.97 nW		
Required singnal level	2.90E+02	photons/puls	2.71 nW (peak)	-55.67	dBm
Allowances and Adjustments				-1.00	dB
Link Margin				**2.80**	**dB**

Detailed Link Table

Transmitter (Jupiter)

Laser (pulsed Q-switched Nd:YAG)

Peak power			10.54 kW	70.23	dBm
Average power	3.00	W			
Wavelength	1.06	um			
Photon energy	1.17	eV			
Word time (including dead time)	70.27	us			
Pulse width	20.00	ns			
Pulse width to slot width ratio	0.80				
Slot width or integration time	25.00	ns			
Dead time	63.87	us			
Duty cycle	0.0031				
Pulse repetition rate	14.23	kHz			
Energy per pulse	0.21	mJ			
Photons per pulse	1.13E+15				
Peak power	10.54	kW			
Electrical-to-optical power efficiency	**12.00**	%			
Prime power	25.00	W			

Transmit Optics

Optics efficiency			**0.80**	-0.97 dB

Telescope (X2000)

On-axis gain			5.29E+11	117.23 dB
Transmit beamwidth	**6.30**	μrad		
Ideal beamwidth	6.30	μrad		
Aperture diameter	**30.00**	cm		
Secondary obscuration	3.00	cm		
Obscuration ratio	10.00	%		
Aperture-to-beamwidth ratio	1.11			
Optical surface quality (1/fraction of wavel	16.00			
Strehl ratio	85.71	%		
Telescope optical losses			0.90	-0.46 dB
Loss from support structure			0.95	-0.22 dB

Pointing

Allowance for pointing loss			**0.80**	-0.97	dB
Jitter (% of beamwidth)	**5.00**	%			
Bias (% of beamwidth)	**5.00**	%			
RMS pointing jitter	0.32	μrad			
Bias pointing error	0.32	μrad			
Mispoint angle	1.14	μrad			
Loss at mispoint angle	0.80				
Expected value of pointing error	0.41	μrad			
Mean loss (Airy beam pattern)	0.94				
Pointing-induced fade probability	0.90	%			

Channel

Space loss			8.89E-39	-380.51	dB
Transmitter to receiver distance	6.00	AU			
Beam size at receiver location	0.89	Earth radii			
Atmospheric loss			0.62	-2.06	dB
Transmission at zenith	**85.00**	%			
Observation angle from zenith	**70.00**	deg			
Air mass	2.92				
Seeing at zenith	9.70	μrad			

Receiver (TMF)

Telescope (10-m telescope)

Gain			8.37E+14	149.23	dB
Aperture diameter	1000.00	cm			
Secondary obscuration	2.00	m			
Obscuration ratio	20.00	%			
Telescope focal length	10.00	m			
Telescope F#	1.0				
Strehl ratio	80.00	%			
Telescope losses			0.80	-0.97	dB

Relay Optics

Filter loss			0.90	-0.46	dB
Acquisition/Tracking split loss			0.80	-0.97	dB
Loss due to redundant detectors			1.00	0.00	dB
Receiver pointing loss			1.00	0.00	dB
Detector truncation loss			1.00	0.00	dB
Actual blur size (FW at $1/e^2$ points)	20.00	um			
Ideal spot size (FW at $1/e^2$ points)	1.96	um			
Other losses			**0.80**	-0.97	dB

Detector (EG&G SLiK APD)

Quantum efficiency	38.00	%
APD gain	39.25	
Detector diameter	1000.00	um
Detector FOV	100.00	urad

Amplifier (Transimpedance Model)

Noise equivalent current (NEI)	0.34	pA/sqrt(Hz)
Detector/preamplifier bandwidth	25.00	MHz

Link Margin

Peak power received at detector		6.50 nW	-51.87	dBm
Required power		2.71 nW	-55.67	dBm
Non-ideal bit synchronization			-1.00	dB
Pulse amplitude variations			-1.00	dB
McIntyre statistics (for APD)			1.00	dB
Code gain adjustments			**0.00**	dB
Allowance for atmospheric effects			0.00	dB
Link margin		1.91	**2.80**	**dB**

Pointing-induced fade probability	0.90	%
Atmosphere-induced fade probability	0.00	%

Coding

Reed-Solomon Coding

Number of symbols (N = M - 1)	255	
Number of information symbols (k)	224	
Minimum distance (Dmin)	32	
Code rate (K/N)	0.88	
Uncoded BER	9.38E-03	
Uncoded word error rate	1.87E-02	
Coded BER	1.00E-06	
Desired coded BER	1.00E-06	

Required Signal Power Calculation

EG&G SLiK APD Detector with Transimpedance Model Amplifier

Detector quantum efficiency	0.38	
Detector ionization ratio	0.007	
Modulation extinction ratio	1.00E-06	
Required peak power	2.71	nW
Signal photons per pulse	290	photons
Phtons per bit	36	photons
Signal PE per pulse (Ks)	110	electrons
Background Noise Power (see below)	2.97	nW
Background PE/slot time (Kb)	151	electrons
Bulk dark current	0.04	pA
Bulk dark electrons (Kd)	0	electrons
Surface dark current	2.00	nA
Gain independent surface dark electrons	312	electrons
Amplifier noise equivalent current (NEI)	0.34	pA/sqrt(Hz)
Temperature	300	K
Effective load resistance	146.65	k-ohms
Gain independent amplifier electrons	55001	electrons
Optimum gain	39.25	
Surface dark electrons (Kds)	0	electrons
Amplifier noise-electrons (Kt)	36	electrons^2
Excess noise factor (ENF)	2.29	
RMS noise electrons (Kn)	381	electrons^2
(1-mer)*Ks/sqrt(2*mer*ENF*Ks+2*Kn)	3.99	a
SQRT(ENF*Ks+Kn)/SQRT(2*mer*ENF*K:	0.91	b
Value of integral in BER eq.	2.46	
BER (M-ary PPM)	9.38E-03	

Background Radiation

Relevant parameters

Receiver area	75.40	m^2
Net receiver transmission	0.46	
Detector FOV	100.00	urad
Detector FOV in solid angle	7.85	nSr
Filter bandwidth	2.0	A
Star in FOV	None	
Irradiance	0.000E+00	W/m^2/A
Background power from star at detector	0.00	pW
Planet in FOV	None	
Receiver to planet distance	1.00	AU
Planet diameter	#VALUE!	km
Angle subtended by planet at receiver	#VALUE!	mrad
Planet radiance	0.000E+00	W/m^2/A/Sr
Planet irradiance	0.000E+00	W/m^2/A
Background power from planet at detectoı	0.00	pW
SkyCondition	Sunny1	
Radiance	5.445E-03	W/m^2/A/Sr
Power at detector from scatter	2.97	nW

Average background power at detect   2.97   nW

a)   Beamwidths refer to full width at 1/e^2 point